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Full L-S Band Telemetry System

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Abstract

This report details a transmission scheme that overcomes the detrimental interference created when two antennas are used on an aeronautical telemetry transmitter, a common practice for overcoming signal obstruction that can occur during air vehicle maneuvering. The development leads to symbol error probability expressions that can be applied to assess the performance of the scheme relative to that of traditional schemes. Representative computational examples demonstrate the potential of the method.

1. Space-Time Coding for Dual-Antenna Telemetry Transmission

The telemetry transmitter detailed above solves one of the problems encountered in aeronautical test and evaluation. Another problem of significant concern is that during aircraft maneuvering, the transmission path for the telemetry data is often obstructed by the aircraft itself. A common solution to this problem is to place a second antenna on the aircraft to ensure the presence of a clear transmission path for all aircraft attitudes. However, when both antennas are in view of the receiver, this arrangement leads to an array interference pattern generally characterized by a large number of transmission nulls. These nulls are clearly detrimental to communication reliability.

The signal variation due to this self-interference is very similar in nature to signal fading created by multipath propagation in wireless communication systems. This observation motivates application of antenna diversity techniques that have been developed for systems operating in multipath environments [1], [2]. One approach that shows particular promise for this application uses a clever transmit diversity scheme in order to reduce detrimental interference [3]. Implementation of the method requires more advanced processing at the receiver, but offers dramatic performance advantages compared to more traditional approaches.

This report develops this method within the context of dual-antenna aeronautical telemetry links. The formulation leads to expressions for symbol error probability that can be used to assess the performance of the method relative to that of traditional techniques. Representative computational examples demonstrate the dramatic improvement in signal reliability offered by the new method. The section concludes with a brief discussion of outstanding issues that require attention before the scheme can be applied operationally.

1.1 Dual-Antenna Transmission Schemes

We begin our study with a careful formulation of the received signals for the traditional and the proposed dual-antenna transmit schemes. Our goal is to obtain a representation that allows analysis of the symbol error rates as well as facilitates a qualitative understanding of the benefit offered by the new approach. In the following, we assume that the antennas 1 and 2 are located at (x_1, y_1, z_1) and (x_2, y_2, z_2) respectively, where the coordinates are expressed in a local coordinate system for the air vehicle. For simplicity of presentation and understanding, we will neglect amplitude and phase variations as a function of angle (i.e. power and phase patterns) for the individual antennas, although it is straightforward to add these variations to the analysis. If the receiving ground station is located at the point (r, θ, ϕ) in spherical coordinates, then the transfer function between the ith antenna, $i \in \{1, 2\}$, and the ground receiver station may be expressed as

$$h_i = e^{jk(x_i \sin\theta\cos\varphi + y_i \sin\theta\sin\varphi + z_i\cos\theta)} \tag{1.1}$$

where $k = 2\pi/\lambda$ is the free-space wavenumber with λ the free-space wavelength.

Consider now transmission using only antenna 1. If the transmitted symbol is denoted as s, the received signal is represented as

$$r_a = h_1 s + \eta \tag{1.2}$$

where η represents the additive white Gaussian noise (AWGN) in the receiver. The received signal energy can be expressed as

$$E_a = \mathrm{E}\{(h_1 s)^* h_1 s\} = \mathrm{E}\{|h_1^2|\}\mathrm{E}\{|s^2|\} = \mathrm{E}\{|s^2|\} = E_s \tag{1.3}$$

where we have used that $|h_1^2| = 1$, $\mathrm{E}\{\cdot\}$ represents an expectation, and E_s is the average symbol energy. The receiver noise power spectral density (PSD) is given as $N_o = \mathrm{E}\{\eta^*\eta\}$, leading to a receive signal-to-noise ratio (SNR) of E_s/N_o. This quantity will be used as a baseline for comparing the performance of the different transmission schemes.

1.1.1 Traditional Transmission

For standard two-antenna transmission, each symbol is simultaneously radiated from both antennas. The received signal may be expressed as

$$r = \frac{1}{\sqrt{2}}(h_1 + h_2)s + \eta \tag{1.4}$$

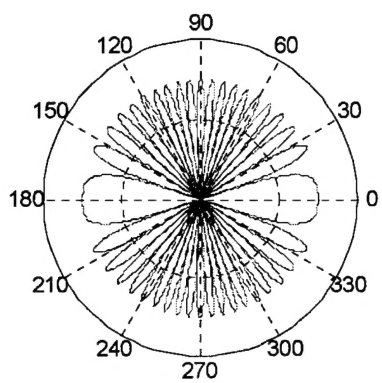
where the factor of $\sqrt{2}$ stems from the fact that the power is equally divided between the two transmit antennas. The received signal energy becomes

$$E_T = \mathrm{E}\left\{\frac{1}{2}[(h_1+h_2)s]^*(h_1+h_2)s\right\} = \frac{1}{2}|h_1+h_2|^2\,\mathrm{E}\{|s^2|\} = \frac{1}{2}|h_1+h_2|^2 E_s \tag{1.5}$$

while the noise PSD is N_o. Therefore, this scheme leads to the received SNR

$$\mathrm{SNR}_T = \frac{1}{2}|h_1+h_2|^2 \frac{E_s}{N_o}. \tag{1.6}$$

For widely-spaced antennas, which is typical of the situation for dual-antenna telemetry transmitters, the coherent addition of the two transfer functions leads to severe nulls in the gain pattern at certain angles. For example, Figure 1 illustrates a plot of this interference pattern as a function of the angle ϕ for $\theta = 90°$ and the antennas separated by 10λ in the x dimension. Clearly, this gain pattern will cause significant reduction in the communication reliability.



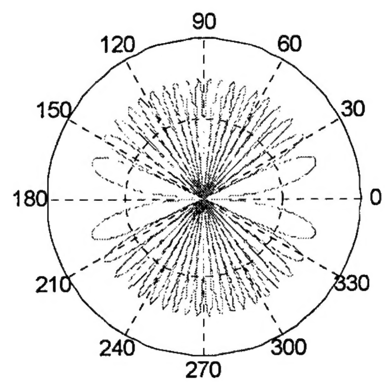


Figure 1: Gain pattern resulting from 2 antennas separated by 10λ for $\theta = 90°$. The two plots are for when the two antennas are in phase and out of phase, respectively.

1.1.2 Diversity Transmission

The transmit diversity scheme proposed here was originally introduced to combat multipath fading for wireless systems. This method, referred to as the Alamouti scheme [3], uses a transmission strategy that spans two consecutive symbol periods. Let the two consecutive symbols be denoted as s_1 and s_2. During the first symbol time, antenna 1 transmits s_1 while antenna 2 simultaneously transmits s_2. During the second time slot, antenna 1 transmits $-s_2^*$ while antenna 2 simultaneously transmits s_1^*. The received signal in the two slots can be expressed as

$$r_1 = \frac{1}{\sqrt{2}}(h_1 s_1 + h_2 s_2) + \eta_1 \tag{1.7}$$

$$r_2 = \frac{1}{\sqrt{2}}\left(h_2 s_1^* - h_1 s_2^*\right) + \eta_2 . \tag{1.8}$$

These equations can be rewritten in the matrix form

$$\mathbf{r} = \begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}\begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} \eta_1 \\ \eta_2^* \end{bmatrix} = \mathbf{Hs} + \boldsymbol{\eta} . \tag{1.9}$$

Using this form, it is simple to show that symbol detection can be performed using the operation

$$\tilde{\mathbf{r}} = \mathbf{H}^{*T}\mathbf{r} = \frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)\mathbf{s} + \mathbf{H}^{*T}\boldsymbol{\eta} . \tag{1.10}$$

During the first symbol time, the signal energy is

$$E_{A,1} = \mathrm{E}\left\{\left[\frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)\right]^2 s_1^* s_1\right\} = \left[\frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)\right]^2 E_s \tag{1.11}$$

while the received noise PSD is

$$N_{A,1} = \mathrm{E}\left\{\frac{1}{2}\left(h_1^*\eta_1 + h_2\eta_2^*\right)^*\left(h_1^*\eta_1 + h_2\eta_2^*\right)\right\} = \frac{1}{2}|h_1|^2\mathrm{E}\left\{|\eta_1|^2\right\} + \frac{1}{2}|h_2|^2\mathrm{E}\left\{|\eta_2|^2\right\} = \frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)N_o \tag{1.12}$$

where we have used independence of η_1 and η_2. An identical result is obtained for the second symbol time. The received SNR for this scheme is therefore equal to

$$\mathrm{SNR}_A = \frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)\frac{E_s}{N_o} \tag{1.13}$$

which, for transfer functions of the form of Eq. (1.1) equals the SNR of the single antenna transmission system. Therefore, this Alamouti scheme can completely remove the detrimental effects of the coherent interference created by the introduction of multiple antennas. It is important to point out that this scheme places most of the complexity and computational burden at the receiver. This is appropriate for aeronautical telemetry applications, since it is difficult to add excessive complexity at the transmitter due to constraints on the size of the telemetry transmitter installed on the air vehicle.

At first glance, the performance gain achievable with this simple transmission scheme may seem surprising. Two comments are warranted concerning this result. The first observation to be made is that by altering the symbols transmitted during the second symbol time, the resulting antenna gain pattern will change (due to the change in the relative phasing between the two antenna signals). For example, for Binary Phase Shift Keying (BPSK), if the two consecutive symbols are such that the antenna pattern is that shown in the left of Figure 1 for the first symbol time, then the pattern will be that shown on the right of Figure 1 during the second symbol time. The superposition of these two

patterns leads to a perfectly omnidirectional pattern. Second, it is important to recognize that obtaining these gains requires that the receiver determine the transfer functions h_1 and h_2. This channel estimation adds computational burden to the system, and can introduce errors that will degrade the performance. Efficient mechanisms for estimating the channel for aeronautical telemetry applications are currently under investigation.

1.1.3 Symbol Error Rate

The formulations in the previous section facilitate the development of expressions for the symbol error rate as a function of the single antenna SNR. To see this, consider first that we have a function that represents the probability of a symbol error $P(\varepsilon)$, where ε denotes the symbol error event and the dependence on SNR is implicitly understood. This function is dependent on the modulation constellation used and noise model assumed. For example, for BPSK and Quadrature Phase Shift Keying (QPSK) with AWGN, this function takes the forms [4]

$$\text{BPSK:} \qquad P_1(\varepsilon) = Q\left(\sqrt{2\frac{E_b}{N_o}}\right) \tag{1.14}$$

$$\text{QPSK:} \qquad P_2(\varepsilon) = 2Q\left(\sqrt{\frac{E_b}{N_o}}\right) \tag{1.15}$$

$$Q(x) = \frac{1}{2}\operatorname{erfc}\left(x/\sqrt{2}\right) \tag{1.16}$$

where E_b represents the average bit energy.

For the Alamouti scheme, the formulations in the prior section demonstrate that for transfer functions of the form of Eq. (1.1), the probability of symbol error will be identical to that given for the AWGN channel. For the traditional transmission scheme, however, we must modify these expressions. Let $f_\ell(E_b/N_o)$, $\ell \in \{1, 2\}$ represent Eqs. (1.14) and (1.15). Examination of Eq. (1.6) suggests that for the traditional scheme, the conditional symbol error probability functions can be expressed as

$$P_\ell(\varepsilon \mid \theta, \phi) = f_\ell\left(\frac{1}{2}\left|h_1 + h_2\right|^2 \frac{E_b}{N_o}\right) \tag{1.17}$$

where the conditional form stems from the dependence of the transfer functions on the angular position of the receiver. If the probability density function (PDF) of these angles for a flight is expressed as $p(\theta, \phi)$, then the average symbol error rate for the flight is given as [4]

$$\widetilde{P}_\ell(\varepsilon) = \int_0^{2\pi}\int_0^{\pi} f_\ell\left(\frac{1}{2}\left|h_1 + h_2\right|^2 \frac{E_b}{N_o}\right) p(\theta, \phi) \sin\theta \, d\theta \, d\phi . \tag{1.18}$$

For the examples below, we assume that the PDF on the angles is uniformly distributed within the plane of rotation. We should also point out that if the transfer functions do not have unity magnitude

over all angles, then a similar operation must be performed to derive the symbol error probability for the Alamouti scheme.

It is important to recognize that this development extends to all modulation schemes for which an error probability expression is available. Therefore, the general conclusions drawn from the results of this analysis are broadly applicable and not restricted to the two modulation schemes chosen.

1.2 Simulation Results

In order to explore the effectiveness of the Alamouti scheme in removing the detrimental interference effects encountered in dual-antenna telemetry transmission, we evaluate the above expressions for several different scenarios. In all simulations, we assume a horizontal antenna spacing of 20 ft., a vertical separation of 8 ft., a frequency of 1.5 GHz, and a ground antenna 400 ft. in front of the aircraft.

For the various aircraft attitude positions, the position of the ground antenna within the air vehicle coordinate frame is computed using Eulerian angle transformations. For a given aircraft altitude, pitch, and yaw, we spin the aircraft one full rotation in the horizontal plane, calculating the transfer functions h_1 and h_2 at each of 36,000 angular sample points. Numerical evaluation of the integral in Eq. (1.18) is then performed using a simple trapezoidal integration rule. It was necessary to use such fine angular sampling in order to capture the behavior in the deep nulls of the interference pattern.

To begin, we examine the simple case when the aircraft and the receiver are in the same plane. Naturally, this is relatively unrealistic, but serves as a straightforward computational example to demonstrate the performance of the new scheme. Figures 2 and 3 demonstrate the probability of symbol error versus the single-bit SNR for BPSK and QPSK modulations, respectively. As can be seen from these plots, the average symbol error rate performance for the traditional dual-antenna transmission scheme is quite poor. In fact, this behavior is very similar to what is observed for channels experiencing severe multipath fading. On the other hand, application of the Alamouti scheme for transmit diversity provides much better performance, achieving symbol error rates of 10^{-6} for SNR values on the order of 10-15 dB. These results also show that BPSK and QPSK exhibit the same trends, indicating that the method is applicable for a variety of modulation schemes.

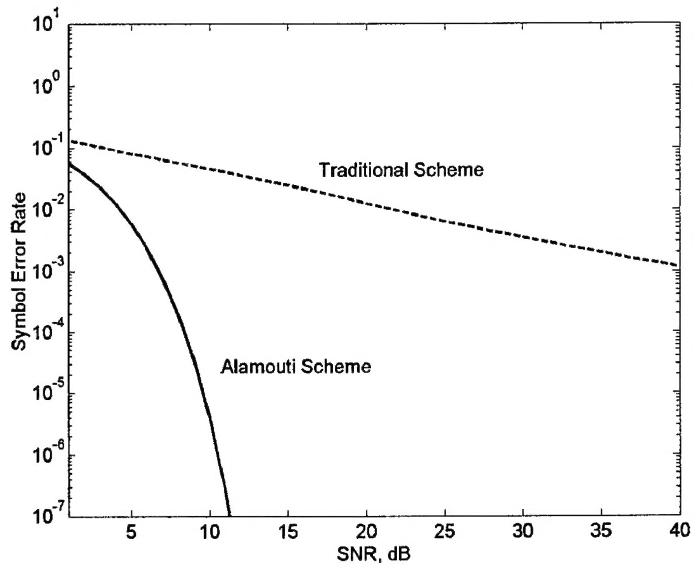


Figure 2: Symbol error rate for Traditional and Alamouti transmission schemes for BPSK modulation with no aircraft elevation.

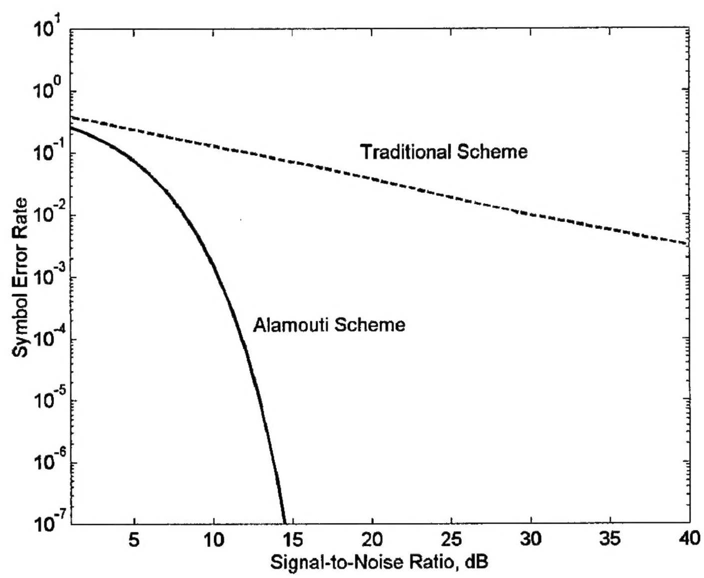


Figure 3: Symbol error rate for Traditional and Alamouti transmission schemes for QPSK modulation with no aircraft elevation.

It is also interesting to examine the behavior of the diversity scheme for a more realistic geometrical configuration. In this case, we assume the aircraft is at an elevation of 2000 ft and at a roll angle of 30° from horizontal. To compute the error probability, the aircraft is then spun in the horizontal plane (relative to the ground coordinate frame). The symbol error probability for this case assuming BPSK modulation is shown in Figure 4. As can be seen, this case exhibits the same behavior as observed in the other examples.

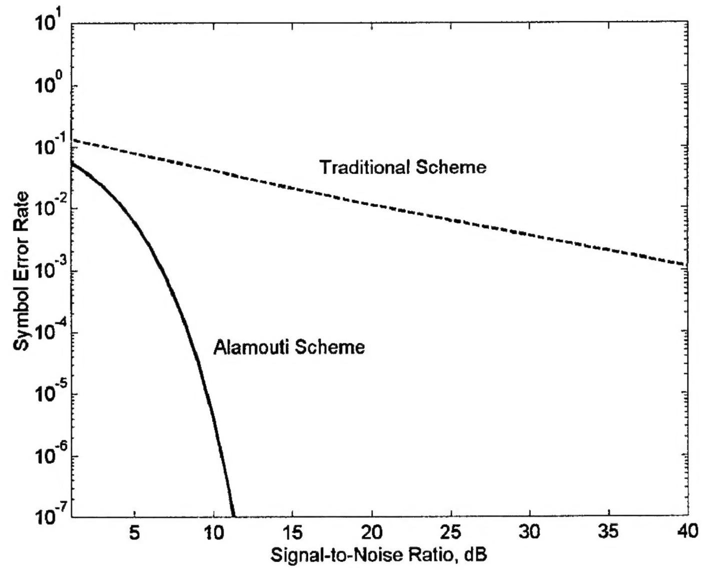


Figure 4: Symbol error rate for Traditional and Alamouti transmission schemes for BPSK modulation with the aircraft at 2000 ft. in elevation and at a 30° roll angle.

1.3 Additional Considerations

While the above developments indicate the potential of the Alamouti transmit diversity scheme for aeronautical telemetry links, there are several issues that must be examined before it can be deployed operationally. These issues will certainly impact the performance of the scheme, and therefore complete evaluation of the method is dependent upon resolution of these issues.

1.3.1 Receive Diversity Implementation

Because air vehicle maneuvering changes the polarization of the transmitted electromagnetic wave, it is important to employ polarization diversity at the receiving station. This implies that the simple transmit diversity scheme must be augmented such that it incorporates two receive channels. This is a relatively straightforward extension of the single receive channel case considered here.

1.3.2 Channel Estimation

Performance of the Alamouti scheme is dependent upon the estimation of the channel transfer functions between the transmit and receive antennas. For an aircraft moving at high velocities, this could be a challenging task since the absolute phase is rapidly varying. However, the task is simplified by the fact that application of the Alamouti scheme depends not on the bulk phase change but rather on the relative phase between the two transfer functions. These phase changes are a result of aircraft attitude variations which occur on a relatively long time scale. Furthermore, if higher order modulation schemes are applied, the receiver will be tracking the bulk phase since this information is necessary for symbol detection.

For high data rates (on the order of 20 Mbits/second), the distance between the two transmit antennas corresponds to a propagation delay that is an appreciable fraction of the symbol period. This means that the two symbols will arrive at the receiver with a significant time offset. Because of this phenomenon, application of the diversity scheme will require compensation for this time shift. This offset will therefore need to be determined during the channel estimation procedure.

2. Conclusions

This report has introduced a new transmit diversity scheme for overcoming detrimental communication conditions created by dual-antenna telemetry transmission. The scheme cleverly alters the symbol transmission such that a two-antenna system can actually achieve the same performance of a single antenna system while overcoming the problem of signal obstruction during air vehicle maneuvering. Symbol error probability expressions have been derived to quantify the relative performance of dual-antenna systems using traditional transmission and the Alamouti scheme. Representative examples demonstrate the dramatic potential impact of this new method.

3. References

[1] Foschini, G. J., and Gans, M. J., "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311--335, March 1998.

[2] Raleigh, Gregory G., and Cioffi, John. M., "Spatio-temporal coding for wireless communication," *IEEE Transactions on Communications*, vol. 46, no. 3, pp. 357--366, March 1998.

[3] Alamouti, S. M., "A simple transmit diversity technique for wireless communications," *IEEE J. Selected Areas in Communications*, vol. 16, pp. 1451-1458, Oct. 1998.

[4] Proakis, John G., *Digital Communications*, Fourth Edition, McGraw Hill, Boston, 2001.